HIGH-ENERGY SCATTERING AND DIFFRACTION: THEORY SUMMARY[a]

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New developments in the theory and phenomenology of high-energy scattering and diffraction that were presented and discussed at DIS2000 are reviewed.

1 Introduction

On the one hand, small-coupling perturbation theory has been successfully applied to a variety of QCD processes. Its validity is well-understood in situations where intermediate states with high virtualities dominate. On the other hand, lattice Monte Carlo simulations provide a powerful first-principles approach to study the low-energy characteristics of the theory, such as the spectrum of hadronic excitations. However, there is still no established method, derived from the Lagrangian of QCD, that describes the high-energy scattering of hadrons. The reason for this is the difficulty to combine non-perturbative effects with the fundamentally Minkowskian physics in the high-energy limit. Thus, it can be argued that the high-energy limit represents one of the most interesting and difficult open problems in the theory of strong interactions. One obvious challenge is the derivation of the high-energy behaviour of hadronic cross sections, which are well-parametrised as $\ln^2 s$ or $s^{0.08}$ (where $\sqrt{s}$ is the cms-energy of the collison), from the known microscopic theory.

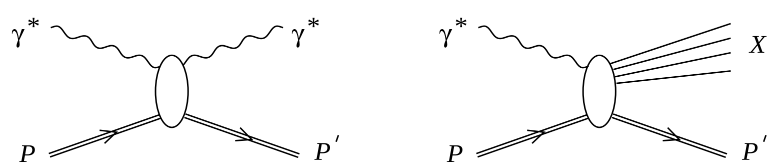

Figure 1: Forward Compton scattering and diffractive electroproduction.

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Diffraction, and in particular the processes of hard diffraction discovered at the CERN S$p\bar{p}$S collider and studied in detail at HERA and the Tevatron, represent a powerful tool for the study of the high-energy limit of QCD. This is illustrated in Fig. 1, where forward Compton scattering, equivalent to the process of deep-inelastic scattering (DIS), is compared to diffractive electroproduction. Obviously, the study of different diffractive final states X provides a wealth of hadronic high-energy scattering data, taking us far beyond the well-known inclusive process of DIS.

2 New Approaches to the High-Energy Limit of QCD

A fundamentally new approach to the high-energy limit of QCD has been advertised by Peschanski [1,2]. The authors suggest using the AdS/CFT correspondence (also known as the Maldacena conjecture) [3] to investigate high-energy scattering in non-Abelian gauge theories. AdS/CFT correspondence claims the equivalence of weakly coupled string theory in an Anti-de-Sitter (AdS) geometry with strongly coupled $\mathcal{N} = 4$ super Yang-Mills theory, which is a conformal field theory (CFT), in 4-dimensional Minkowski space. Further, to make the connection with the realistic case of confining gauge theories, the authors use Witten's proposal [4] that a confining gauge theory is dual to string theory in an AdS black hole background. In the gauge theory, the high-energy scattering of two dipoles can be calculated from the correlation function of two Wilson loops. Using AdS/CFT correspondence, the calculation of the latter can be reduced to a minimal surface problem in an AdS black hole background. The results obtained so far show reggeization with unit intercept [2].

A very different unconventional approach to high energy scattering has been suggested by Kharzeev and Levin [5,6,7]. They start from the leading order BFKL ladder diagram and emphasize the NLO contribution where the one-gluon rungs are replaced by pairs of gluons. Then, focussing on the soft region, these gluon pairs are replaced by pion pairs. The coupling to the vertical gluon lines of the ladder is fixed by employing the QCD anomaly relation

$$\theta^\mu_\mu = \frac{\beta(g)}{2g}\, F^{a\,\alpha\beta} F^a_{\alpha\beta} \tag{1}$$

and calculating the trace of the energy momentum tensor θ^μ_μ in terms of the pion degrees of freedom in chiral perturbation theory. After all ladder diagrams with two-pion rungs are summed, a soft-pomeron-like behaviour $\sim s^\Delta$ emerges. The intercept $\Delta = (1/48) \ln M_0^2/m_\pi^2$ comes out approximately right if the matching scale M_0^2, introduced by using chiral perturbation theory, is taken in the range $4 \div 6$ GeV^2, in agreement with sum rule analyses.

As emphasized by Kharzeev, diffractive glueball production provides an interesting testing ground for this new picture of the pomeron [5].

3 γ^*-γ^* Scattering at High Energy

The total cross section of two highly virtual photons represents a unique testing ground for perturbative methods in high-energy scattering because the underlying process is the interaction of two small colour dipoles. The process is expected to include a kinematical region where the BFKL summation techiques are applicable.

Recent progress relevant to NLO BFKL calculations [8] was discussed by Lipatov, who emphasized the enormous simplifications of the NLO BFKL kernel arising in $\mathcal{N} = 4$ SUSY QCD and possible close relations between BFKL and DGLAP [9,10]. Furthermore, Lipatov noted the good description of $\gamma^*\gamma^*$ data in NLO BFKL achieved by using a non-Abelian physical renormalization scheme together with BLM scale fixing [11]. However, other methods to modify the naive NLO corrections to BFKL, which are extremely large, do also exist [12].

The problems of the BFKL method justify the attempt to account for the data, which lies far above the Born term prediction, by other means. Naftali [13,14] presented a calculation taking into account hard-soft and soft-soft contributions, which are also present in γ^*-γ^* processes. Although significant enhancements were found, they are not sufficient to account for the data when both photon virtualities are large. Donnachie reviewed the recent phenomenological approach of the 'two pomerons' [15,16], which includes the well-known reggeon and soft pomeron trajectories and a phenomenological hard pomeron with an intercept ~ 0.44. This approach describes successfully γ-γ and γ^*-γ cross sections, but is below the data in the γ^*-γ^* case.

4 Diffractive Electroproduction

A large part of the diffractive data at HERA can be characterized by the diffractive structure function F_2^D, which describes the process $\gamma^* p \to p' X$ (cf. Fig. 1). In addition to the conventional kinematic variables of DIS, Q^2 and $x = x_{\rm Bj}$, the process is characterized by M, the mass of the diffractive final state X. Alternatively, the variables $\beta = Q^2/(Q^2+M^2)$ or $\xi = x_{I\!P} = x/\beta$ can be used. Now, $F_2^{D(3)}(x, Q^2, \xi)$ is defined precisely as $F_2(x, Q^2)$, but on the basis of a cross section that is differential in ξ as well as in x and Q^2. Elastic vector meson production, to be discussed in more detail below, is obtained by appropriately specifying the final state X. For recent theoretical reviews of diffractive DIS see refs. [17,18].

Diffraction occurs if the hadronic fluctuation of the incoming virtual photon scatters off the proton without destroying its colour neutrality. At leading order, the fluctuation is a $q\bar{q}$ pair, and its interaction can be parametrized by the dipole cross section $\sigma(\rho)$, where ρ is the transverse size of the dipole [19]. A QCD-improved parametrization of the dipole cross section which carefully implements its relation to the gluon distribution in the region of small ρ and avoids unitarity violations associated with the strong growth of the gluon distribution at small x was presented by McDermott [20,21].

Diffractive parton distributions [22], denoted here by $df_i^D/d\xi$, characterize the probability of finding a parton in the proton under the condition that the proton remains intact. In this framework, which is firmly rooted in perturbative QCD, the diffractive cross section reads

$$\frac{d\sigma(x,Q^2,\xi)^{\gamma^*p\to p'X}}{d\xi} = \sum_i \int_x^\xi dy\,\hat{\sigma}(x,Q^2,y)^{\gamma^*i}\left(\frac{df_i^D(y,\xi)}{d\xi}\right), \qquad (2)$$

where $\hat{\sigma}(x,Q^2,y)^{\gamma^*i}$ is the total cross section for the scattering of a virtual photon characterized by x and Q^2 and a parton of type i carrying a fraction y of the proton momentum.

Royon presented a parametrization of F_2^D as well as a QCD fit based on the DGLAP evolution of diffractive parton distributions [23,24]. A novel feature of this fit is the subtraction of higher twist contaminations at large β. It is interesting that the famous 'peaked' gluon of previous H1 analyses [25] seems to be disfavoured.

Schäfer [26] discussed results for $F_2^{D(3)}$ at small β, obtained in the colour-dipole Regge-expansion approach and stressed the relevance of unitarity corrections for the ξ dependence.

Goulianos has suggested a simple parametrization [27] of the F_2^D data at HERA, which is based on the ansatz $d^3\sigma/d\xi\,dx\,dQ^2 \sim F_2^h(x,Q^2)/x/\xi^{1+\epsilon}$ with a 'hard' structure function F_2^h.

An important new result concerning the charm contribution to F_2^D was presented by Bartels [28]. At leading order, diffractive charm production is realized by $c\bar{c}$ and $c\bar{c}g$ final states. Except for the large-β region, the latter component dominates because it allows for soft colour-singlet exchange. The new results presented by Bartels extend previous calculations of $c\bar{c}g$ production, where the $p_\perp$ of the gluon was assumed to be much smaller than the $p_\perp$ of the quarks (strong $p_\perp$ ordering), to general kinematic configurations excluding, however, the case of soft gluons.

5 Diffraction at Hadron-Hadron Colliders

A frequently discussed issue in hard diffractive processes where either one or both colliding hadrons remain intact is the question whether a simple connection with the partonic description of diffractive DIS can be found. As emphasized by Royon, the hadronic data undershoots HERA based expectations by a large factor [23,29], which is indeed expected from the simple geometrical picture of the collision of two extended soft objects. Thus, a fundamentally new theoretical approach to this type of hadronic processes appears to be necessary. Timneanu [30] reported the successful description of both HERA and Tevatron gap events by using a Monte Carlo implementation of a Soft-Colour-Interaction model based on the generalized area law. Also, as presented in the talk by Cox [31,32], HERA and Tevatron data characterized by a gap between two jets can be described by LLA BFKL within the HERWIG Monte Carlo, if a fixed $\alpha_S = 0.17$ is adopted and if multiple scattering for the underlying event is taken into account. The interesting process of Higgs (or dijet) production in double rapidity gap events was discussed by Khoze [33]. He presented refined calculations in a perturbative approach, which, however, lead to cross sections considerably smaller than those predicted by some non-perturbative models. Close explained [34] how the pomeron can be studied in hadron collisions at low momentum transfer by measuring the ϕ and t dependence for different ($J^{PC} = 0^{\pm +}, 1^{++}, 2^{++}$) mesons.

6 Elastic Meson Production

Elastic vector meson production $\gamma^* p \to Vp$ is a rich field, both theoretically and exprimentally. For large photon virtualities Q^2 and/or heavy mesons (with large mass M_V) this process constitutes a nice laboratory to study diffractive hard scattering. At small ξ the production amplitude factorizes in the fluctuation of the virtual photon, the elastic scattering of the $q\bar{q}$ (or $q\bar{q}g, \ldots$ in higher orders) off the proton, and the formation of the final state (vector) meson (V): $\mathcal{A}(\gamma^* p \to Vp) = \psi^{\gamma}_{q\bar{q}} \otimes A_{q\bar{q}+p} \otimes \psi^{V}_{q\bar{q}}$. At leading order the diffractive (colourless) exchange is realized by a pair of gluons [35]. In the usual collinear factorization approach the amplitude $A_{q\bar{q}+p}$ is then proportional to the gluon density in the proton $\xi g(\xi, \mu^2)$ at some effective scale $\mu^2 \sim (Q^2 + M_V^2)/4$.

Recent calculations as reported by I. Ivanov [36] and Martin [37] improve on these approximations (see also [17]). Firstly, the transverse momentum of the exchanged gluons is taken into account by applying the so-called k_T-factorization and using the *unintegrated* gluon distribution $f(\xi, k_T^2)$, where k_T is the transverse momentum of the exchanged gluons. Secondly, even in the case of forward scattering the need to transform a spacelike photon into a timelike vector

meson forces the kinematics to be non-forward, and the usual parton (gluon) distributions have to be replaced by *skewed* (also called non-forward or off-diagonal) parton distribution functions (SPDF). These are generalizations of the normal PDFs (without direct probabilistic interpretation) and follow their own, new evolution equations. A method to construct corresponding exclusive evolution kernels at NLO was reported by Freund [38]. In this work explicit diagrammatic two-loop calculations are avoided by using conformal $\mathcal{N} = 1$ SUSY Yang-Mills constraints together with known two-loop DGLAP kernels.

Within the perturbative two-gluon-picture, elastic (electro-) production of light and heavy vector mesons can be calculated in fair agreement with experimental data as long as Q^2 and/or M_V^2 provide a hard scale of several GeV^2. As the cross section depends on the gluon distribution squared, the process $\gamma^* p \to V p$ may serve as a particularly sensitive probe of the gluon at small ξ. To achieve this ambitious goal the theoretical uncertainties should be decreased further. In addition use should be made of the different available observables, i.e., Q^2 and energy dependence of the total cross sections for different mesons, σ_L/σ_T, the ratio of longitudinal to transverse photon induced production, and maybe even the full spin density matrix of ρ or J/ψ production measurements. One particular source of uncertainty in the theoretical description is the meson wave function. As shown by I. Ivanov [36] different wave function models lead to quite different results, especially for σ_T, and the wave function is expected to play a significant role in the production of excited vector mesons compared to ground states.

On the other hand, as demonstrated by Martin [37], the basic features of elastic vector meson production are mainly controlled by the photon wave function and the gluon distribution and can therefore be well predicted in the framework of Parton-Hadron-Duality (PHD). This approach uses open $q\bar{q}$ pair production, integrated over an appropriate mass interval and projected on the quantum numbers of the meson under consideration, thus avoiding the meson wave function completely. Even σ_L/σ_T, which is poorly described in most other models, is in agreement with HERA data.

Another field where the use of perturbative QCD in the framework of the two gluon picture can be justified is diffractive meson production at large momentum transfer t. New interesting results were reported by D. Ivanov [39,40]. He obtained large contributions to high-t light vector meson photoproduction from a – normally highly suppressed – chiral odd $q\bar{q}$ component, where the photon couples to the quarks via the magnetic susceptibility of the vacuum with a surprisingly large coefficient.

A particularly interesting possibility for observing the odderon, i.e., the $C = P = -1$ partner of the pomeron, in the context of diffractive meson

production has been suggested by Dosch [41,42]. Addressing the fundamental question why the odderon is not seen in the difference between pp and $p\bar{p}$ cross sections, the authors suggest that the reason lies in the quark-diquark structure of the proton. If this is the case, then the diffractive production of pseudoscalar mesons at HERA with proton breakup in the final state should provide an ideal testing ground for the odderon. Employing a stochastic vacuum based approach in the description of the soft t-channel exchange [43], a prediction of $\sigma_{\gamma p \to \pi^0 X} \approx 300$ nb with estimated model uncertainties of $\pm 50\%$ was given.

7 Conclusions and Outlook

The high-energy asymptotics of hadronic cross sections belong to the few phenomenologically relevant and not yet calculable implications of known quantum field theories. Thus, high-energy scattering and diffraction remain among the least well understood and therefore most interesting fields in QCD. Progress has been reported in may directions, with work ranging from simple phenomenology to elaborate multi-loop calculations. Given the fast and continuous improvement of data and the rich interplay between theory and experiment, we experience an exciting time for this fundamental area of research.

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